

Stirlin*GUIDE*

(GRAPHICAL USER INTERFACE FOR DESIGN AND EDUCATION OF STIRLING TYPE MACHINES)

Manual and Tutorial for Version 1.0

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1 Software Overview

StirlinGUIDE (version 1.0) is a graphical tool that illustrates the design and elucidates concepts of Stirling Cryocoolers and Stirling-type Pulse Tube Refrigerators (PTRs).

The computer programs currently available for Stirling type machines help in designing and optimizing Stirling type cryocoolers. However, the available software are only intended for the serious researcher and knowledgeable hobbyist to conduct high-end research work. The pre-existing computer applications are unable to assist various young students who are about to take off on their research career. These budding researchers are faced with conceptual challenges in understanding the fundamentals of cryogenics and cryocoolers. This brings to the fore a need for a pedagogical tool that facilitates the understanding of cryogenics and provides a simple explanation about the working of cryocoolers along with a design tool that could be used to approximate first order performance of cryocoolers in order to carry out further parametric studies.

This software, the Graphical User Interface for Design and Education of Stirling type machines (StirlinGUIDE), is one which can be used as an interactive tool to understand the basic working mechanism of Stirling type machines. StirlinGUIDE is a Graphical User Interface (GUI) built using MATLAB® and can be used to study Stirling cryocoolers and Stirling type Pulse Tube Refrigerators. The MATLAB code for the Stirling Cryocooler uses assumptions based on cyclic analysis. The isothermal model along with cyclic analysis has been utilized for devising the algorithm for PTR with an inertance tube. Along with cyclic analysis, the interface also provides a visualization of the specific cryocooler and a learning module for the user. The user interface can thus, be utilized by students as well as young faculty as a teaching aid and a design tool. The design model involved in writing the algorithm and the features of StirlinGUIDE are discussed in detail later in Section 2.

StirlinGUIDE provides a comprehensible platform for non-computer specialists to attain results for a particular cryocooler based on the required design and performance parameters. It also offers wide-ranging graphical illustrations which can assist in experimental courses in Cryogenic Engineering. A decent interpretation of the results can help in optimization of the cryocooler.

The current version of StirlinGUIDE requires a recent version of MATLAB (preferably R2009a and later) only. No toolboxes are required. The software works in Windows.

2 Design Model

StirlinGUIDE utilizes various design models for the simulation and analysis of Stirling type Cryocoolers. The design parameters and operating conditions are entered by the user using which StirlinGUIDE computes the cooling effect and power input with some basic assumptions.

Cyclic Analysis:

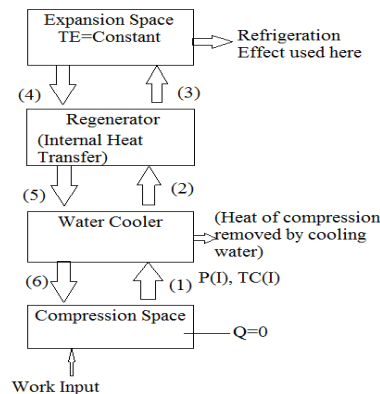
Complete cycle is divided into several intervals at which pressures, volume variations, mass flow rate variations etc. are calculated which are then applied to loss analysis.

Certain assumptions taken into consideration for the analysis are listed below:

- The gas behaves as a Perfect Gas
- Piston and Displacer move sinusoidally
- Whole system has a constant pressure
- Cooler dead space temperature is mean of inlet and outlet temperatures
- Compression process is adiabatic whereas expansion is isothermal
- Regenerator mass flow rate is the logarithmic mean of that in the compression and expansion spaces

The volume variations for the expansion and compression spaces are first computed on the basis of the inputted parameters and dimensions. Pressure at each interval is then calculated which is utilized to evaluate temperatures for the corresponding intervals with the assumption of adiabatic compression in which Newton-Raphson method is utilized as a mathematical tool. A correction factor is then found to correct the previous pressure values.

Ideal Power input and Ideal Refrigeration effect is then calculated by simple integration using trapezoidal rule. The procedure for cyclic analysis is shown by a model for a Stirling cryocooler in the figure below.

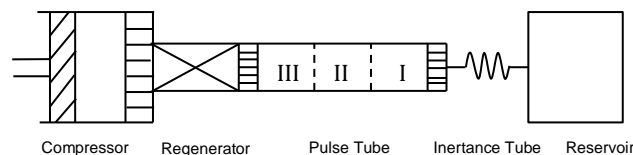


Cyclic analysis for Stirling cryocooler

Isothermal Model:

The isothermal model is proposed for the investigation of orifice PTR. Since the isothermal model does not account for the losses in the pulse tube, a second order isothermal model is used that includes losses in an orifice PTR by using cyclic analysis. Similar methodology is used for an inertance tube PTR.

The simple isothermal model can be illustrated using the schematic of an inertance tube PTR as shown in the figure below. The gas within the pulse tube can be split into three parts. Part III is the cold part that flows from regenerator and expands to give out work. Part I of the gas is the hot part which flows to the reservoir and absorbs work. Part II is the moving gas displacer in the middle part which replaces the solid piston in a split Stirling refrigerator. This part is always inside the pulse tube.



Schematic of inertance tube PTR

Some of the assumptions of the isothermal model are as follows:

- The gas is an ideal gas and there is no gas leakage through the piston seal
- There is no fluid resistance
- Pressure at all points in the system remains the same at any instant
- Gas in middle part of the pulse tube is adiabatic while the other parts are isothermal

To carry out this analysis, a pressure-volume cycle of 360° is divided into several small time intervals. For each interval, ideal gas law is applied and pressure for corresponding interval is obtained. Applying conservation of mass for sections I, II and III, all the volumes and temperatures are obtained. Getting the values of temperature and volumes, the ideal refrigeration effect and ideal power required are calculated. The ideal parameters are then modified considering the various identifiable losses.

Loss Analysis:

Mass flow rates are different because of different regenerator, cooler and condenser dead spaces. Variation in mass fraction of gas inventory for each space is calculated for each interval. These are converted into mass flow rates by multiplying by molecular weights and speeds.

The losses taken into consideration are:

- Regenerator Ineffectiveness Loss: Present due to the ineffectiveness of the regenerator resulting in slightly higher temperature in the expansion space
- Shuttle Heat Conduction: Displacer absorbs heat from the hot end and gives it out at the cold end
- Temperature Swing Loss: Accounts for constant change in temperature of the regenerator matrix
- Pumping Loss: Continuous pressurization and depressurization of the cooler results in the gas present in the gap between the expander and the wall to flow in and out of this gap, thus, reducing the refrigeration
- P-V Loss: Due to pressure drop in the regenerator, cooler and evaporator, the pressure at the expansion space is lesser than the compression space
- Loss due to conduction in solid members
- Additional power requirement due to pressure drop in the cooler, the regenerator and the condenser because of flow friction

3 Installation

The current version of StirlinGUIDE only requires MATLAB and none of the toolboxes are necessary. StirlinGUIDE works in Windows.

The files provided should be copied to a directory or folder on your hard drive. For example, in Windows: `C:\StirlinGUIDE`. You may choose any other directory, but all remaining instructions in this manual will assume the directory names used here.

Start MATLAB and go to the directory where the software is installed. Type `StirlinGUIDE` at the MATLAB command line to start the software.

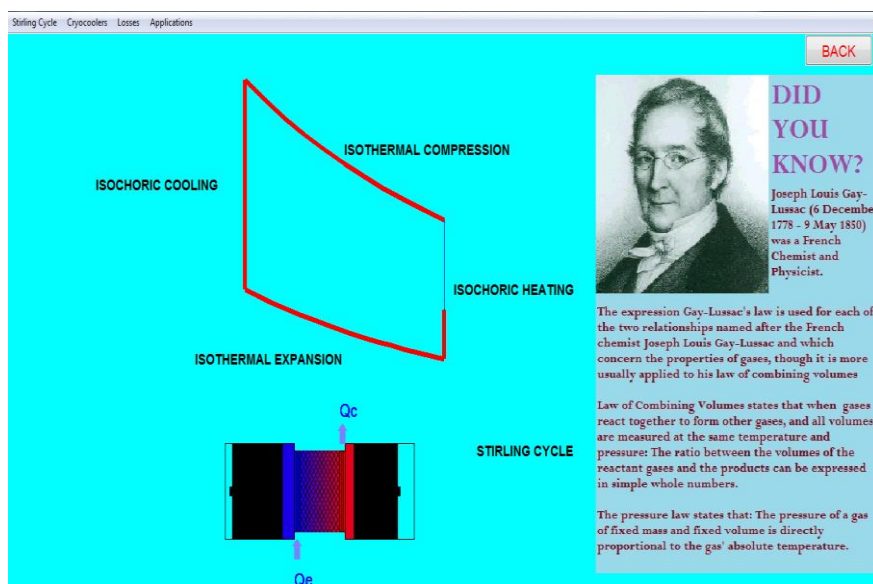
Please contact the authors if you experience any problems regarding the installation – see Section 5 for contact details.

4 Tutorial Case Study

In StirlinGUIDE, a GUI is used to display the simulations and calculations done in the algorithm. The graphical interface is preferred over the command-line interface since entering numerous commands to complete certain operations may become cumbersome or error-prone. The GUI consists of two modules: (a) Educational (b) Design. The two modules are described further.

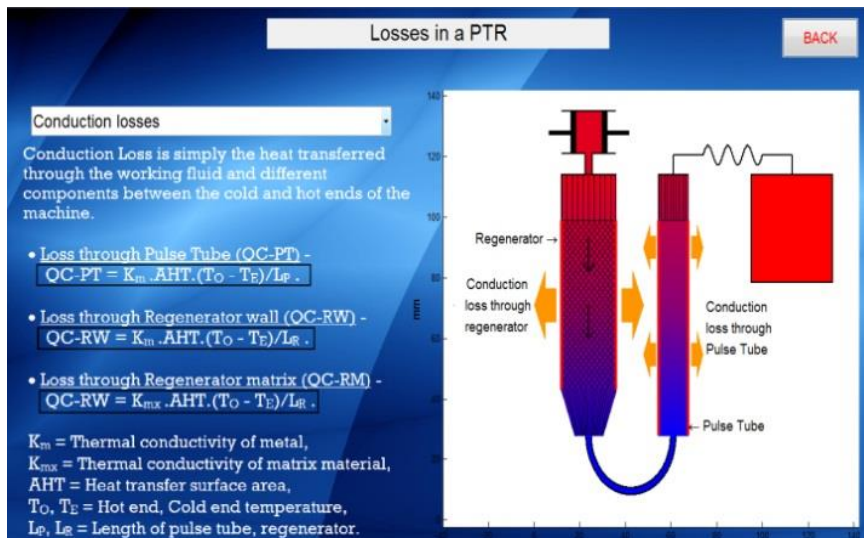
Educational Module:

On selecting the 'Learn' button on the welcome screen, you shall reach the Educational Module of StirlinGUIDE. It is a user friendly interface designed to help an individual understand the fundamentals of cryogenics and various cryocoolers. The module explains the working mechanism of the Stirling cycle with vivid animations and describes the different types of cryocoolers including their components; advantages; disadvantages; practical applications etc. The figures below are screenshots from the Educational Module.



The working mechanism of a Stirling cycle in the educational module

Several losses incurred in cryocoolers have also been explained both by text and animation. The figure below gives a glance of one of the losses that take place in a cryocooler. Interesting trivia is also shown to the user in the form of various "Did You Know's" simultaneously.



Conduction Losses occurring in a PTR as a part of the educational module

Design Module:

Along with the educational tool, StirlinGUIDE also has a design section. The Design section helps the operator to simulate and compute results for a cryocooler. Shown below are the input screens for Stirling cryocooler and PTR.

Parameters

Average Pressure: 25 bar Freezer Wall Temperature: 77 K
 Crank Phase Angle: 72 ° Engine Speed: 1450 RPM
 Mechanical Efficiency: 70 % Cooling Water Temperature: 293 K

Dimensions

Piston Diameter: 70 mm Displacer Diameter: 70 mm
 Piston Stroke: 53 mm Displacer Stroke: 53 mm
 Piston Clearance: 0.5 mm Displacer Clearance: 0.5 mm
 Piston Length: 70 mm Displacer Length: 70 mm

Regenerator

Outer Diameter: 127 mm Inner Diameter: 76.2 mm
 Length: 76.2 mm Screen Wire Diameter: 0.08 mm
 Pitch: 0.127 mm Mesh Density: 63.662 per cm

Cooler

Inner Diameter of Tubes: 1.6 mm Inner Diameter of Tubes: 1 mm
 Length of Tubes: 100 mm Length of Tubes: 76 mm
 No. of tubes per cylinder: 200 No. of tubes per cylinder: 180

ALPHA BETA GAMMA

Power Required: W Net Refrigeration: W COP:

Inputs

Stroke Length: 5 mm
 Length of Regenerator: 56 mm
 Diameter of Regenerator: 28 mm
 Length of Pulse Tube: 70 mm
 Diameter of Pulse Tube: 20 mm
 Length of Inertance Tube: 2.2 m
 Charging Pressure: 17 bar
 Cold End Temperature: 70 K
 Operating Frequency: 50 Hz

Outputs

Total Input Power (W) W
 Net Refrigeration Power (Q) W
 COP
 Pressure Ratio

Losses

Loss due to regenerator inefficien... W

Graphs

Pressure vs. Angle

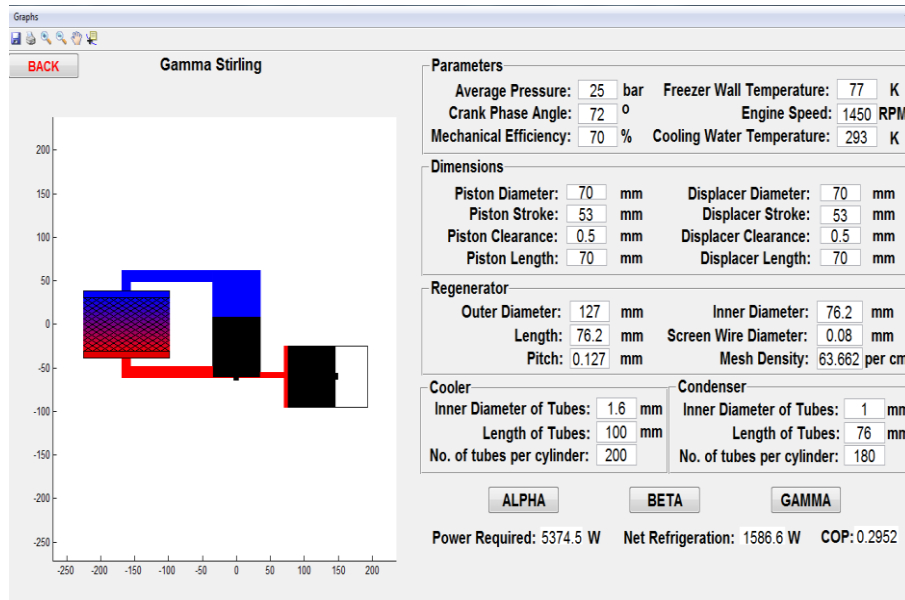
U-tube PTR Enter BACK

Input Screen for Stirling cryocooler (left) and PTR (right)

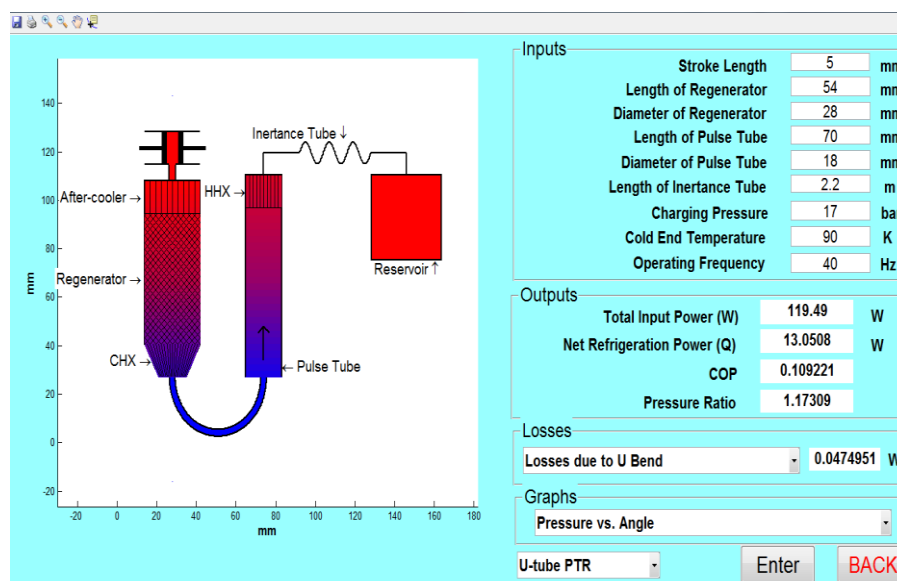
The user can choose between the Stirling cryocooler and the PTR. For the Stirling machine, one can select the alpha (α), beta (β) or gamma (γ) configurations. The Inline and U type configurations can be used while designing a PTR with inertance tube. There is another advanced option that allows the user to simulate and study a Two Stage U type PTR.

The program first interrogates the user to acquire the necessary data input. These include the design parameters such as average pressure, temperature, phase angle etc. and the dimensions of regenerator, displacer, piston etc. Using that information, StirlinGUIDE

determines the performance of a cryocooler by calculating the parameters, for instance, the net refrigeration effect, total work input and COP and displays them on the screen. An animation of the cryocooler with the particular input dimensions also can be viewed alongside the results as evident in the figures below.



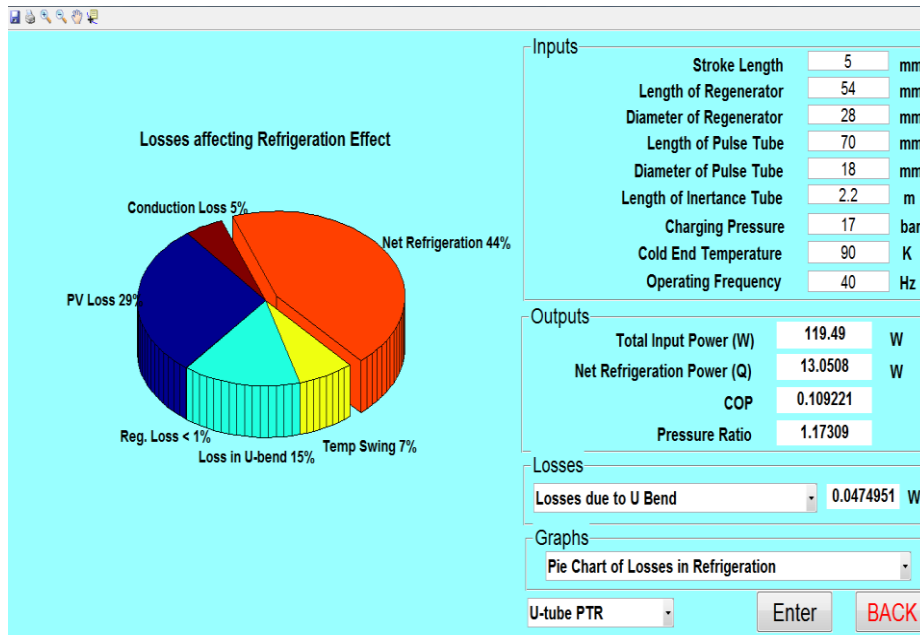
Model of a Gamma Stirling machine



Simulation and Computations of a U-type PTR

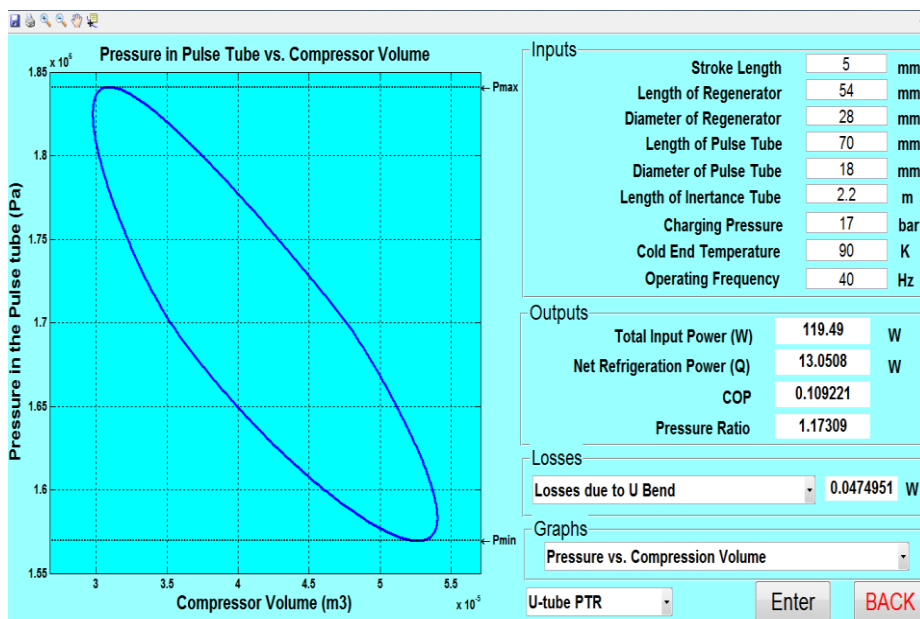
The losses in the cryocooler are computed using the aforementioned analyses and one can select from among various losses which can be viewed in a separate segment on the screen. There is also a feature wherein the losses are displayed in the form of a pie chart. The chart helps the user recognize the dominating loss and modify the design accordingly. Such a pie chart for losses in a U Type PTR is shown below. If the output matches the requirements, the operator can proceed to save the results in a suitable format or to print them along with

the input data and the simulation. The user may continue to vary the operation and design parameters and observe the outputs till the requirements are met.

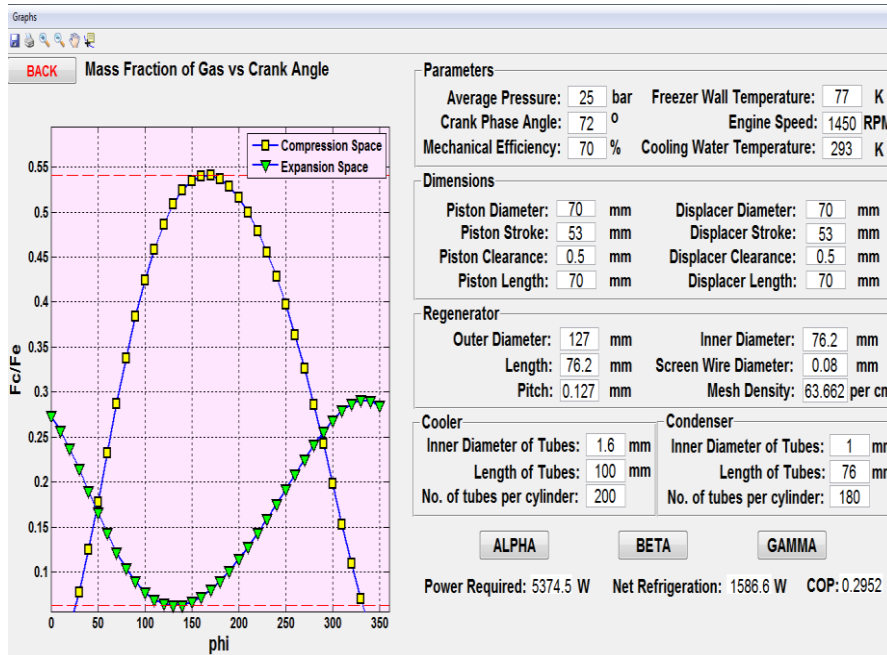


Pie Chart for Losses affecting Refrigeration Effect in a U Type PTR

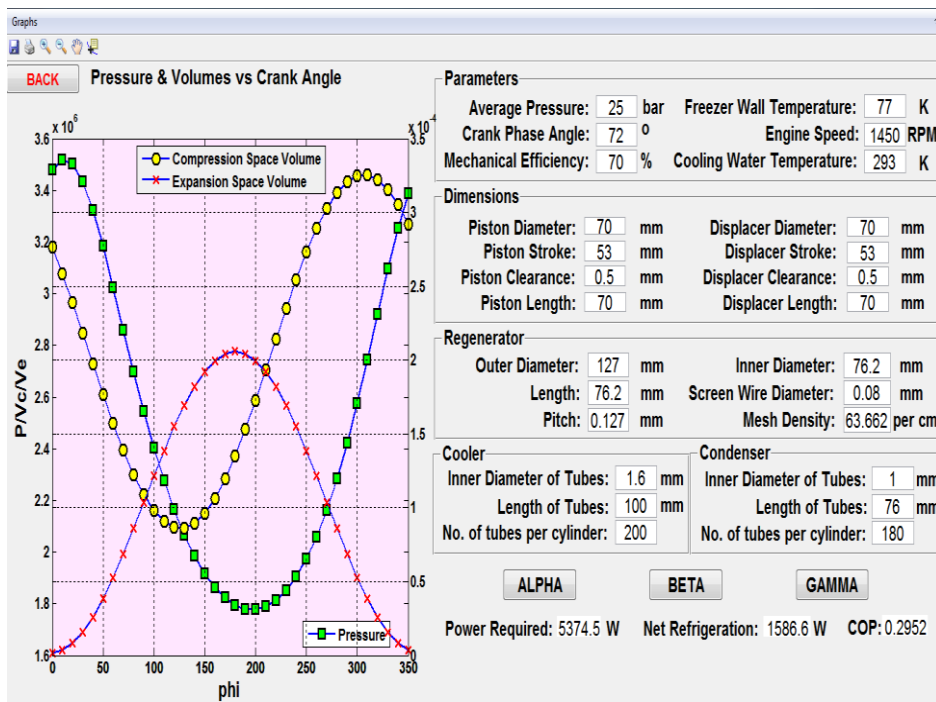
The user can then advance to examine the graphical data. For a given cryocooler, the change in pressure, volume and mass flow rates with crank angle and variation of pressure with volume (P-V diagrams) at different locations in a cryocooler can be analyzed by the plotting tool which displays various graphs. In Stirling cryocoolers, gas flow distribution can be explained by graphs between mass fraction of gas in compression or expansion space and crank angle. Some graphical illustrations are displayed below.



Pressure in Pulse Tube vs. Compressor Volume in a PTR

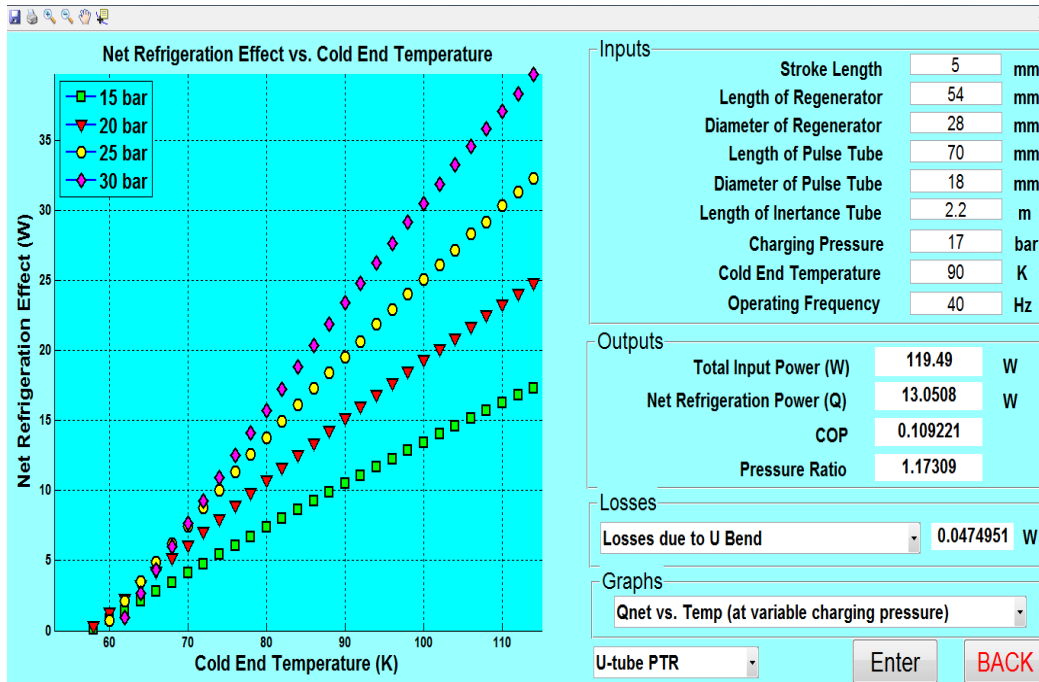


Mass Fraction of Gas in compression and expansion space vs. Crank angle in a Stirling cryocooler



Pressure & Volumes vs. Crank Angle for Stirling Cryocooler

The variation of the output by altering the design and operating parameters can be studied through several graphs. For instance, we can assess the change in net refrigeration effect (Q) and net input power with the minimum temperature attained (T), dimensions of regenerator, etc. at different pressures. Such a case is visible in the figure below.



Q vs. T for Varying Pressures for a PTR

5 Technical Support

Technical support of StirlinGUIDE is provided to all users. Feel free to contact the appropriate person by email or telephone regarding any queries that you may have. Any suggestions for new features and improvements to the software are most welcome.

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References

Atrey, M. D., Bapat, S. L. and Narayankhedkar, K. G., (1990), Cyclic Simulation of Stirling Cryocooler, *Cryogenics*, **30**, 341-346.

Zhu, S.W. and Chen, Z.Q., (1994), Isothermal Model of Pulse Tube Refrigerator, *Cryogenics*, **34**, 591-595.

Atrey, M.D. and Narayankhedkar, K.G., (2000), Development of Second order isothermal model of orifice type pulse tube refrigerator, *International Cryogenic Engineering Conference*, **18**, 519-522